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Validating and Improving the DeltaQ Duct Leakage Test

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ABSTRACT

The DeltaQ duct leakage test has been developed over the past several years as an improvement to existing duct pressurization tests. It focuses on measuring the air leakage flows to outside at operating conditions that are required for energy loss calculations for duct systems, and infiltration impacts. The DeltaQ test builds on the standard envelope tightness measurement technique of a blower door by repeating the tests with the system air handler off and on. This study uses detailed laboratory measurements to validate the DeltaQ test procedure and calculations. The laboratory measurements used a purpose-built test chamber coupled to a duct system typical of forced air systems in U.S. homes. Special duct leaks with controlled and monitored airflow were designed and installed in the duct system. This test system enabled us to systematically vary the duct and envelope leakage and to accurately measure the duct leakage flows for comparison to DeltaQ test results. The laboratory testing has also led to enhancements to the DeltaQ calculations that increase the accuracy of the leakage measurement.

INTRODUCTION

Distribution system leakage is a key factor in determining energy losses from forced air heating and cooling systems. (See for example Cummings et al 1990.) Several studies (Francisco and Palmiter 1997 and 1999, and Andrews et al. 1998) have shown that the air distribution system efficiency cannot be reliably determined without good estimates of duct air leakage. Specifically, energy calculations require the air leakage flow to the environment at operating conditions to be known. The test methods currently used in ASHRAE Standard 152 (ASHRAE 2003) and ASTM (1994; E1554) either precisely measure the size of leaks (but not the flow through them at operating conditions), or measure these flows with insufficient accuracy. This and other methods to measure thermal distribution system leakage are discussed in Walker et al. (2001 and 1998), Francisco (2002), Andrews (1998) and ASHRAE (2003).

The DeltaQ test uses a simplified physical model of the distribution system leakage that uses prior knowledge regarding how distribution systems function in residential buildings. The test procedure builds on existing envelope leakage measurement techniques to infer thermal distribution system leakage at the normal operating conditions.

This study builds on previous studies; Walker et al. (2002, 2001and 1998), by performing a systematic laboratory evaluation of test accuracy and by making improvements to the analytical methods used to derive the air leakage flows from the measured air flow and pressure data. This study evaluates the DeltaQ test against a truth standard approaching the accuracy of the known leakage values for this test chamber.

BUILDING ENVELOPE LEAKAGE

Building envelope leakage has been thoroughly studied over many years because it relates to the envelope that encloses the building and acts as a pressure boundary[1]. Empirically, the flow of individual building leaks has been shown to have the non-Darcy functional form in Equation 1:

$$Q = C\left(P\right)^{n} \qquad (1)$$

where
Q = *volumetric airflow,*
C = *leakage coefficient,*
P = *pressure across the leak, and*
n = *pressure exponent.*

[1] . See for example, the Air Infiltration and Ventilation Centre, http://www.aivc.org for resources on infiltration and air leakage.

Physically the exponent must be between half and unity, corresponding to inertial flow and fully developed laminar flow. Sherman (1992) and Walker et al. (1998) have shown that power-law behavior with an intermediate exponent is to be expected from short path-length leaks and is physically described by developing laminar flow. Sherman and Dickerhoff (1998) have shown that the exponents are clustered near 2/3 (0.65±0.08)

The standard technique for measuring building envelope leakage is fan pressurization (ASTM E779 1999) during which a set of steady-state pressures is built up by use of a fan and the airflow vs. pressure data is fit to Equation 1. The device used to pressurize the building is colloquially known as a "Blower Door", and its use and history are described by Sherman (1995).

DISTRIBUTION SYSTEM LEAKAGE

In many parts of the U.S. distribution system leakage is a more important problem than envelope leakage in terms of energy, indoor air quality and peak power usage (Modera 1993). Understanding the process, being able to quantify the effect and being able to predict benefits of leakage reduction require a robust model of the process. Most distribution systems, especially in the climates that require cooling, can be characterized by Figure 1.

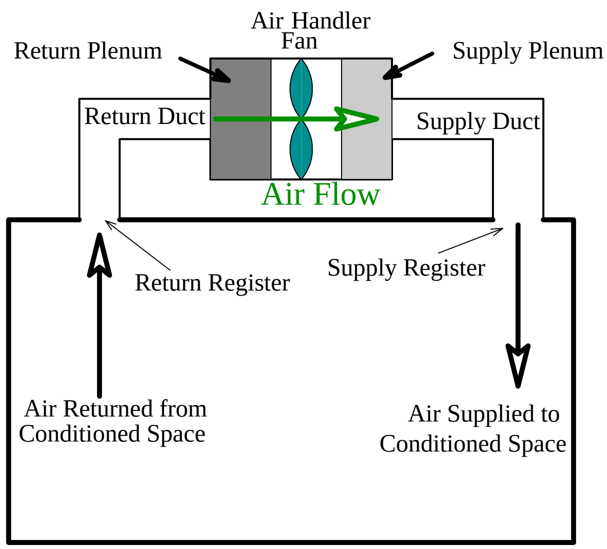

Figure 1: Illustration of a typical residential air distribution system.

In most smaller buildings at least some part of the air distribution system extends outside of the pressure boundary formed by the envelope so that leakage from those parts of the system represent a loss of conditioned air from the building.

The physically important quantities to determine are the supply and return airflows through the leaks (to the environment) under normal operating conditions.

Because there is an air handler inducing airflow through the distribution system, the pressures in the distribution system will be quite different from those across the building. In particular, the return side of the system will generally be under negative pressure and air leakage enters the duct system. Conversely, the supply side is at a positive pressure and supply air leakage leaves the duct system.

DEVELOPMENT OF DELTAQ

The development of the DeltaQ model comes from splitting the total building leakage to outside into three parts, the envelope, the supply ducts and the return ducts. When the air handler fan is on these leaks all see different pressures. The full development of the DeltaQ Equation can be found in Walker et al. 2001, and is given in Equation 2:

$$\Delta Q(P) = Q_s\left[\left[1+\frac{P}{P_s}\right)^{n_s} - \left[\frac{P}{P_s}\right)^{n_s}\right] - Q_r\left[\left[1-\frac{P}{P_r}\right)^{n_r} + \left[\frac{P}{P_r}\right)^{n_r}\right] \qquad (2)$$

where ΔQ is the difference in airflow through the blower door required to keep the enclosure at a fixed pressure relative to outside when the air handler is switched on,

and the subscripts "s" and "r" refer to the supply side and return side respectively. Note that to maintain the proper sign conventions we have used the notation that

$$[P)^n \equiv P \cdot |P|^{(n-1)}$$

Thus, $\boldsymbol{Q_s}$ is the supply leakage flow and $\boldsymbol{P_s}$ is the characteristic pressure for the supply ducts. All pressures are expressed relative to outside the house and $\boldsymbol{P_s}$ and $\boldsymbol{P_r}$ are expressed as positive values. In most cases, the normal operating supply and return leakage flows are not equal, resulting in a net pressurization or depressurization of the house. This, usually small, pressure is often ignored but later we will discuss a correction for this effect on the DeltaQ analysis. It is also assumed that all measurements are taken at the same air density.

This expression is linear in the two most important parameters, namely the supply and return leakage airflows, but it does have in principle four other unknown parameters: the operating pressures and exponents of the supply and return leakage. In most systems, there is more than one leak site and operating pressure. $\boldsymbol{P_s}$ and $\boldsymbol{P_r}$ are then the two pressures that best characterize the individual pressures across all supply and return leaks.

ANALYSIS OF THE DELTAQ MODEL

A robust inverse model must be able to accurately determine the parameters of interest within the likely range of application. For a non-linear model, it is quite likely that there will be ranges of the parameters in which the model will not work well, so there is some value in examining the limits of Equation 2 with respect to the pressure and exponent parameters.

Consider the limit in which the applied pressure is much larger than the induced supply or return pressures:

$$\Delta Q(P >> P_{s,r}) \approx Q_s\left[n_s\left[\frac{P}{P_s}\right)^{n_s-1}\right] - Q_r\left[n_r\left[\frac{P}{P_r}\right)^{n_r-1}\right] \tag{3}$$

Equation 3 shows that for any exponent less than unity the DeltaQ value will go asymptotically to zero when the applied pressure is much larger than the characteristic supply and return leakage pressures. In circumstances where the leakage is very large (on the order of 50% of fan flow or more), the true DeltaQ relationship is more complex and its limits are less well defined. However, precision diagnostics are not required to detect duct failures of this magnitude.

We also consider the opposite limit in which the applied pressure is much smaller than either of the characteristic leakage pressures:

$$\Delta Q(P << P_{s,r}) \approx Q_s\left[1 + n_s\frac{P}{P_s} - \left[\frac{P}{P_s}\right)^{n_s}\right] - Q_r\left[1 - n_r\frac{P}{P_r} + \left[\frac{P}{P_r}\right)^{n_r}\right] \tag{4}$$

In this limit the DeltaQ equation does not provide any information except for the imbalance flow, $\boldsymbol{Q_s}$ - $\boldsymbol{Q_r}$, . If all of the data is in this regime, the DeltaQ procedure will fail, but some data in this regime can be helpful.

The exact limits of when the DeltaQ equation breaks down are going to depend on data quality. The more precision in the measurements of pressure and flow, the wider the range of pressures for which we will be able to extract useful information. However, it is clear that if the range of applied pressures is far away from the characteristic supply and return pressures, we will not get good information from Equation 2. If we have prior knowledge about the supply and return pressures and the exponent, we are not limited in this regard.

We can explore the nature of the DeltaQ equation by plotting Equation 2 for some intermediate conditions. Figure 2 contains a plot of the kinds of DeltaQ curves we might expect for a distribution system that had leakage in the supply only, and the leak is at three different leak pressures: 0.060, 0.141 and 0.281 in. water (15 Pa, 35 Pa and 70 Pa). The inflection point in the DeltaQ curve corresponds to these leak pressures. For a supply leak the inflection point is found during envelope depressurization as the sign of the pressure difference across the leak changes from positive to negative. The flow direction through the leak goes from out flow, through zero (at the inflection point) and then becomes inflow because the whole system is depressurized more than the positive pressure existing in the supply ducts during normal operation. Similarly, for return leaks, there will be an inflection point at a positive envelope pressure difference.

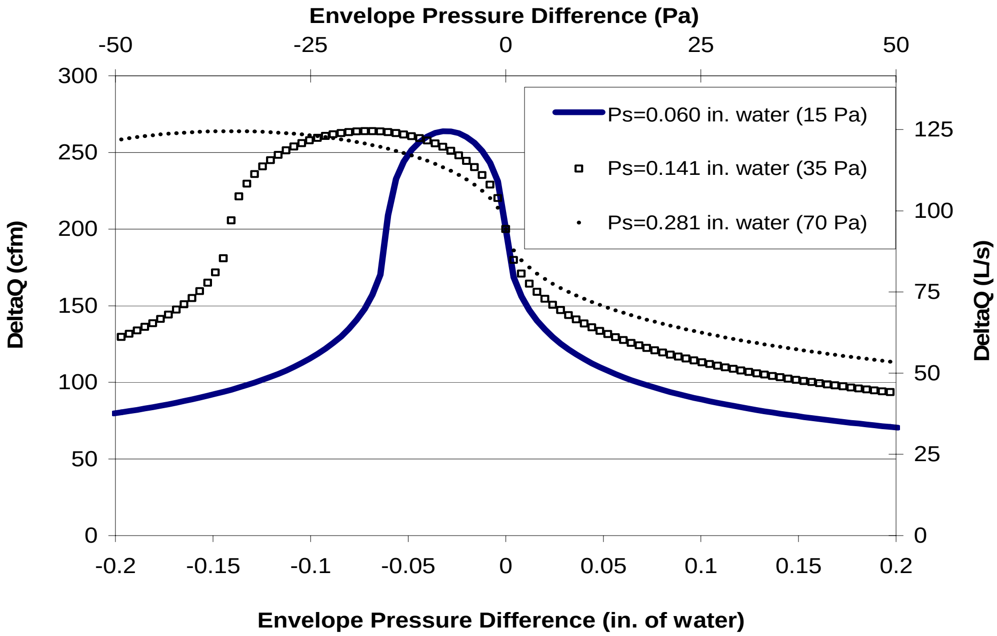

Figure 2: Supply leakage DeltaQ curves with different supply leakage pressures.

In Figure 2 we show three curves, which represent the identical air flows at operating conditions, but are for three different characteristic pressures (i.e. P_s). The shape of the curve in the region of interest is quite different (Andrews 2002) suggesting that we can use experimental data to determine this parameter. The positive and negative pressure asymptotes go to zero for all physical combinations of parameters. The exception occurs if the leakage exponent is unity. If the pressure flow leakage relationship is linear, the DeltaQ curve becomes a horizontal line and the only quantity that can be determined from the data is the difference between supply and return leakage.

Leak Pressures

The standard DeltaQ model assumes that there is a single supply or return leakage pressure and thus there is one equivalent leak on each side; this is sometimes assumed to be the plenum pressure. A single leak pressure leads to the characteristic inflection point and shape of Figure 2. In reality there are going to be many leaks in the duct system. Even if all the leaks were in the plenum, the plenum pressure might not be the appropriate pressure because of inertial effects.

In a real duct system the leaks will be distributed at multiple pressures. A measured DeltaQ curve for such leaks would have multiple inflection points and have a more stair-step pattern rather than a single maximum and minimum.

If we knew in advance the size and locations of all the leaks we could devise an exact DeltaQ expression to match it, but we are interested in the reverse modeling problem of trying to infer properties from measurements. Thus we will continue to assume that there is a single leak on each side with the understanding that we are finding an equivalent leak with the same pressure and flow relationship as the actual system. By doing so we are finding the effective leakage properties of the system which may or may not represent the conditions of an actual leak.

Use of Prior Knowledge

The DeltaQ Equation (2) ostensibly has six unknown parameters that need to be resolved. The typical experiment, however, generates around ten to twenty independent data points, each at a different envelope pressure difference, leaving only a few degrees of freedom and decreasing the statistical power of the model.

One way to improve this situation would be to take data over a wide range of envelope pressures. Another is to use prior knowledge about the parameters of interest to either remove them from the analysis or to restrict their values. Let us review what is known about these quantities.

- $\underline{\boldsymbol{Q_{s,r}}}$**:** We know both physically and by definition, that the leakage flows must be non-negative. They also have a physical maximum equal to the flow through the air handler, but, since typical leakage rates are around 10% of air handler flow, this maximum does not often play an important role.
- $\underline{\boldsymbol{P_{s,r}}}$**:** The supply and return leakage pressures must be positive (as defined here). Their maximum value would be the pressure just on either side of the fan, which is normally represented by their respective plenum pressures. Because of the opportunity for leakage and larger impact of the leaks at higher pressure, we would normally expect the leak pressure to be in the upper half of its range. Experience to date has borne this assumption out.
- $\underline{\boldsymbol{n_{s,r}}}$**:** Physically the exponents must be between half and unity, but as mentioned earlier existing pressurization data has shown that the exponent tends to be close to 0.6 for air distribution systems. The only notable exception to this generalization is when there is a large hole caused either by a disconnection or as in our experiments with added plenum leaks. In such a case, the exponent is much closer to 0.5.

Prior information provides several alternative analysis methods. The one that makes the most extreme use of priors is to fix the exponents at 0.6 and to use measured plenum pressures as being representative for the leaks. We tried this approach on field tests of over 100 different distribution systems (Walker 2001), and the approach appeared to work successfully for the majority of cases.

There were, however, a minority of cases that either did not fit well at all or produced seemingly unreasonable results for the leakage flows. We investigated those cases further and concluded that for most of them either the supply or return pressure used in the DeltaQ analysis was not appropriate.

We then considered treating the pressures as additional variables in the fit to see if that improved the fit and physical significance of the result. This lowered the total leakage for the whole data set by 8%. Figure 3 is an example of how this approach improved the analysis for one of the problem cases. The inflection point in the fitted pressure curve occurs at 0.076 in. water (19 Pa). It is apparent that actual supply leakage in this case was at an effective pressure of only about 1/3 of the plenum pressure of 0.229 in. water (59 Pa).

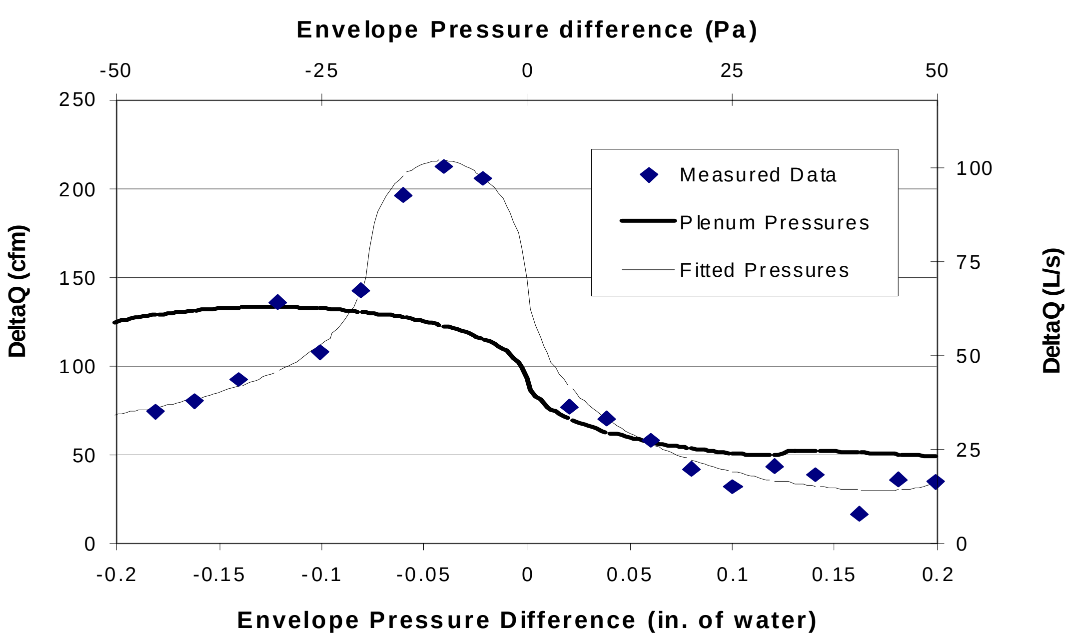

Figure 3: DeltaQ analysis comparing plenum pressures with fitted pressures.

Using this analysis approach improved the fit significantly in many cases and did not lead to any convergence problems. It also has the practical advantage of eliminating the effort to make the independent measurement of plenum pressures. Walker et al. (2002) compared the approach of fixed vs. variable pressures for 87 California systems and found that the RMS difference in leakage flows was about 30%.

Allowing the characteristic pressures to be found as part of the fit resulted in about 10% lower leakage flows. Usually the characteristic pressure found from the fit was lower than the measured plenum pressure. This does not always have to be the case as the measured plenum pressure is not always the maximum pressure and the characteristic pressure is an "effective" one and may not correlate to an actual pressure in the system.

Regardless of how leak pressures are determined, there are some potential biases inherent when using them in the DeltaQ model—caused by some of the simplifying assumptions. In the following sections we examine a few of the key assumptions and develop corrections for some of these biases:

CORRECTING PRESSURE BIASES IN THE DELTAQ MODEL

The terms $\boldsymbol{Q_s}$ and $\boldsymbol{Q_r}$ are coefficients of the model and represent the supply and return air leakage to outside flows when the house pressure is zero. The normal operating house pressure may not be zero because of a combination of large unbalanced leakage and a tight building envelope. To figure out the actual leakage flow at operating conditions, we must correct for the actual house pressure during operation.

The pressure offset, P, can be measured or calculated. If the offset is due primarily to the imbalance in the flow, it can be estimated from the model parameters directly:

$$P = \left(\frac{Q_r - Q_s}{C_{env}} \right)^{1/n_{env}} \tag{5}$$

where the subscript "env" refers to the building envelope.

In either case, we can use that value to get the correct flows from the model parameters:

$$Q_s^{actual} = Q_s \left[1 + \frac{P}{P_s} \right)^{n_s} \tag{6}$$

$$Q_r^{actual} = Q_r \left[1 - \frac{P}{P_r} \right)^{n_r} \tag{7}$$

For most situations the pressure offset is small compared to the leak pressures, and this correction is minor.

CORRECTING DUCT RESISTANCE BIASES IN THE DELTAQ MODEL

In the development of DeltaQ, we assumed that the pressure at the leak would rise or fall by the same amount that the house pressure rises or falls. This assumption ignores the impact of flow resistance in the ducts. In reality there is always a pressure drop induced by the air flowing in the ducts and this causes a bias.

The bias depends on the resistance of the duct system, the airflow that goes through the duct system during the tests, and the relative size and location of the leaks. In the DeltaQ test, the actual pressure at the leak is offset from the nominal one used above because of these factors. If we knew these pressure offsets, the DeltaQ expression could be modified to remove the bias as follows:

$$\Delta Q(P) = Q_s \left[\left[1 + \frac{P - \delta P_s^{on}}{P_s} \right)^{n_s} - \left[\frac{P - \delta P_s^{off}}{P_s} \right)^{n_s} \right] - Q_r \left[\left[1 - \frac{P - \delta P_r^{on}}{P_r} \right)^{n_r} + \left[\frac{P - \delta P_r^{off}}{P_r} \right)^{n_r} \right] \tag{8}$$

The nominal DeltaQ analysis tells us something about the location and size of the leaks, but it does not directly provide any information about the resistance of the duct system. Since we know the approximate leakage pressure and flow, we could estimate the duct resistance if we knew the air flow through the ducts. The DeltaQ technique itself does not provide such a measurement, but there are a variety of methods of doing so and it is not unusual for the flow through the air handler to be required for other reasons.

We will need to have a rough estimate of the fraction of the fan flow represented by the supply and return leaks under normal operating conditions. This ratio is a common way of expressing duct leakage:

$$\phi_{r,s} \equiv {Q_{r,s}^{actual}} \big/ {Q_{air-handler}} \tag{9}$$

As will be seen below, the solutions for these offsets are themselves functions of the model parameters; this technically makes the expressions recursive, which often requires an iterative numerical approach to the solution. Because of the inherent (and required) non-linearities of this problem, iteration is a common feature. In general, we expect the offsets will scale with the applied (house) pressure, but not necessarily linearly.

Fan-Off Analysis

When the fan is off, but there is an applied pressure in the house, there is a pressure drop between the leak site and the house caused by the resistance in the ducts relative to the resistance in the leak. Since the house pressure can reach the leaks through both supply and return registers we can generally assume that not much air goes through the air handler when the handler is off. Thus, the flow that goes through the ducts must be the flow that goes through the leaks and we can get a relationship for the pressure offset:

$$(1-\phi_{r,s})\left[\frac{\delta P_{r,s}^{off}}{P_{r,s}}\right)^{n_{duct}} = \phi_{r,s}\left[\frac{P-\delta P_{r,s}^{off}}{P_{r,s}}\right)^{n_{r,s}} \tag{10}$$

We can start out by solving exactly for some special points. There is no pressure offset (bias) when there is no applied house pressure. If both exponents were unity, making the equation linear, this expression could be solved to yield a factional pressure offset that was independent of the location of the leak and was simply equal to the fractional leakage flow. As we know, however, the DeltaQ technique works because of non-linearities, so that solution is not likely to be very interesting.

If we assume that the exponent of the duct system airflow resistance and the exponent of leaks are equal, we can generate a closed form solution as follows:

$$\frac{\delta P_{r,s}{}^{off}}{P} = \frac{\phi_{r,s}^{1/n_{r,s}}}{(1-\phi_{r,s})^{1/n_{r,s}} + \phi_{r,s}^{1/n_{r,s}}} \tag{11}$$

In general, the exponent of the flow through the duct, n_{duct}, has been measured as being very close to 0.5 for typical flows, and so we shall assume henceforth that it is. For comparison, the exponent of duct leakage has been observed to normally lie in the range 0.5 to 0.65. If we consider this more general case and calculate the pressure offset (as a fraction of house pressure) vs. house pressure (normalized by the leak pressure) we obtain the results shown in Figure 4.

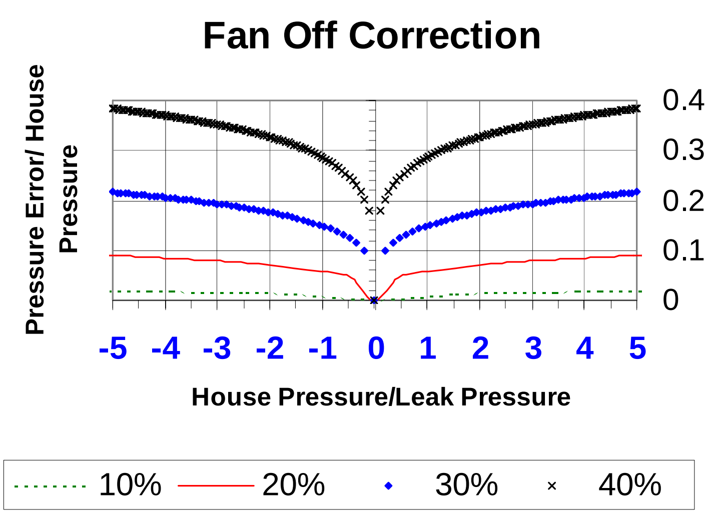

Figure 4: Pressure offset for fan-off condition as a function of applied house pressure. The four curves represent four different duct leakage amounts as a fraction of fan flow. We have assumed an exponent of 0.5 for the duct system and 0.65 for the leaks.

We can see that if the leakage is below 20% of fan flow or the applied pressures are below the typical leak pressures, the offset (i.e. error) is not very big.

Fan-On Analysis

When the fan is on, there is still a pressure offset when the house pressure is applied, but it is more complicated because the leak is already under pressure from the air handler. The leakage flow is now equal to the difference between the fan flow and the flow through the duct, so the defining relationship becomes:

$$1-(1-\phi_{r,s})\left[1\pm\frac{\delta P_{r,s}^{on}}{P_{r,s}}\right)^{1/2}=\phi_{r,s}\left[1\mp\frac{P-\delta P_{r,s}^{on}}{P_{r,s}}\right)^{n_{r,s}} \qquad (12)$$

where the top sign applies to the return and the bottom sign to the supply.

Equation 12 assumes that a supply leak does not affect the flows or pressures on the return side of the duct system and vice versa. Although this assumption has not been rigorously evaluated, Walker (2004) showed that return plenum leakage changed by less than 5% of the leakage flow, when the supply leakage varied from 5 to 25% of the fan flow. So for the experiments discussed here, where the return leaks are also in the return plenum only, the assumption is a good one. However, for more general application, where return leaks are at lower pressures, more work needs to be done to evaluate this assumption.

One interesting case, which is seen in the data, is when the house pressure is enough to change the direction of flow through the leaks:

$$P=\mp\frac{P_{r,s}}{(1-\phi_{r,s})^2}\leftrightarrow\frac{\delta P_{r,s}{}^{on}}{P_{r,s}}=\mp\frac{\phi_{r,s}(2-\phi_{r,s})}{(1-\phi_{r,s})^2} \qquad (13)$$

This part of the DeltaQ curve is often where a lot of the information comes from so it is important to consider the correction in this area.

Figure 5 illustrates the range of fan-on pressure corrections for a typical configuration.

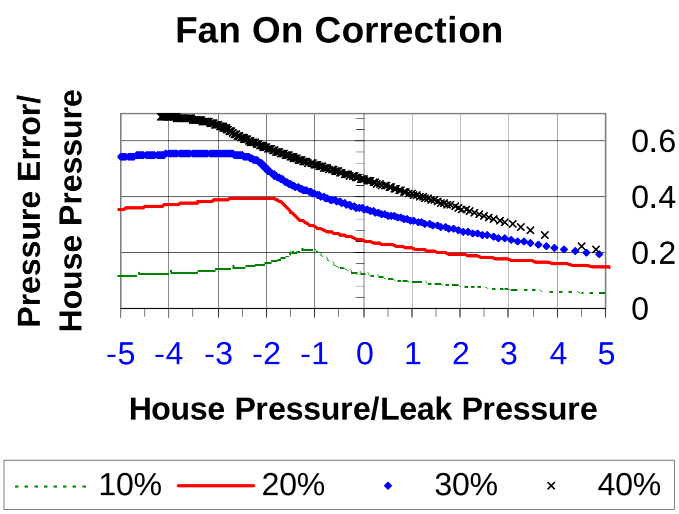

Figure 5: Pressure offset for fan-on condition as a function of applied house pressure (for a supply leak). The four curves represent four different leakage amounts as a fraction of fan flow. We have assumed an exponent of 0.5 for the duct system and 0.65 for the leaks.

This set of curves is much more complicated than the fan-off curves because of the non-linear interactions of the fan-induced flows with the house-pressure induced flows. These interactions change with the leakage fraction and the applied pressure. These offsets are also larger than the fan-off offsets.

LABORATORY MEASUREMENTS

A proper analysis of any simplified model requires that it be tested against data. Ideally, we would like to compare inverse model predictions against a truth standard. Previous laboratory testing (Walker et al. 2001 and 2002) demonstrated generally good agreement between the DeltaQ predictions and the known leakage. Because of limitations of the test facility, these measurements had a limited range of duct and envelope leakage, and it was impossible to attain a true zero leakage condition. To overcome these difficulties a test chamber and complete duct system was built inside a warehouse.

The test chamber

The test chamber is a 32 ft long × 8 ft wide × 8 ft high (9.5m×2.5m×2.5m) wood framed structure (see Figure 6). The chamber is mounted above a crawl space that contains the duct system. The test chamber was built inside a warehouse and is completely sheltered from any outdoor weather. For ease of use two blower doors were mounted in one wall of the chamber – one to pressurize the structure and one to depressurize it.

Figure 6: Completed test chamber inside warehouse showing the return duct connection and blower door fans, but before supply duct installation.

The background leakage of the test chamber with the two blower doors and duct system combined was about 90 cfm at 0.2 in. water (42 L/s at 50 Pa). About two thirds of this background leakage is leakage through the blower doors themselves. Two envelope leakage configurations were used in our tests: “tight” (590 cfm at 0.2 in. water) (280 L/s at 50 Pa), and “normal” (1870 cfm at 0.2 in. water)(880 L/s at 50 Pa).

The duct system

The duct system has 10 supply registers and one return. Deliberate calibrated leaks were mounted at the register boots and the supply and return plenums. The register boot leaks were designed to have the same pressure exponent as typical duct leaks (i.e., 0.6) while the plenum leaks were through flow meters with pressure exponents of 0.5. The air handler flow is measured using a flow nozzle in line with the return duct and averaged 980 cfm (460 l/s).

Four leakage levels were tested: none, low (about 6% of fan flow), medium (about 22% of fan flow) and high (about 50% of fan flow). These leakage levels were achieved for several combinations of boot, supply plenum and return plenum leaks.

Figure 7 is an example of DeltaQ data taken using this apparatus and shows the blower door data with the air handler on and off as well as the DeltaQ data. The example shown is for “medium” leakage with leaks at the supply and return plenums and at “normal” envelope leakage.

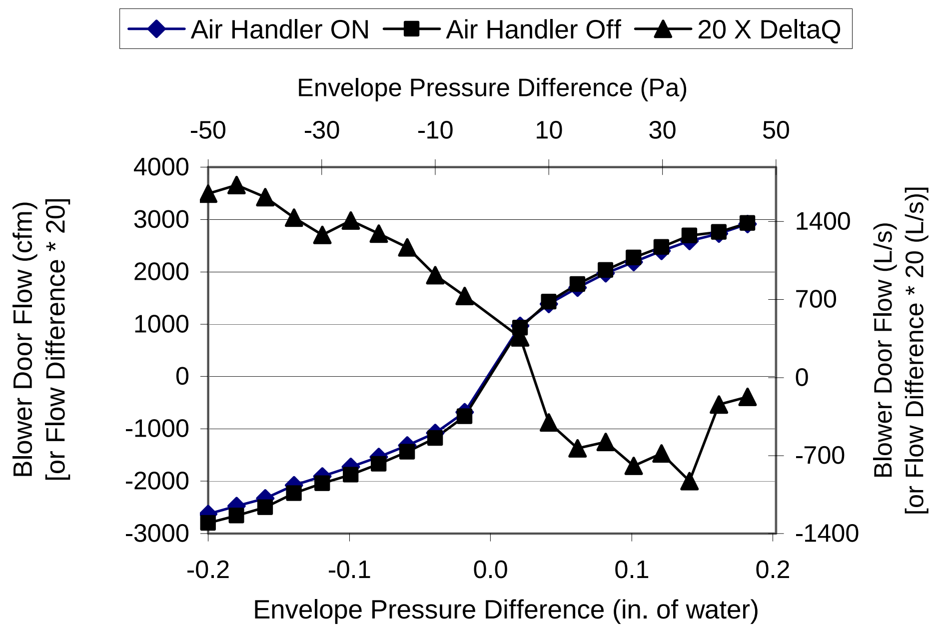

Figure 7: Typical flow vs. pressure relationships for DeltaQ experiment.

TEST CHAMBER MEASUREMENT RESULTS

When the envelope pressure range is large enough to include a definite maximum value in the DeltaQ data points (and possibly the inflection point in the depressurization data can be seen) then new values of $\boldsymbol{P_s}$ could be determined when the duct resistance correction is applied as seen in Figure 8.

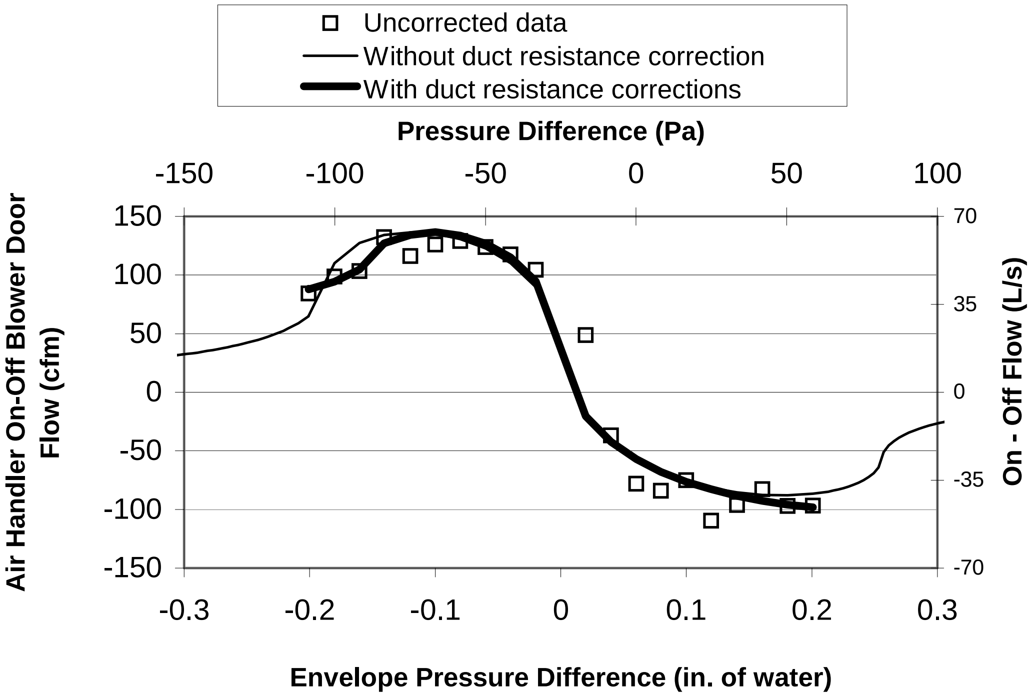

Figure 8: The DeltaQ equation with and without $\delta P_{r,s}$ corrections for a case where the fit finds different $\underline{P_s}$ values. The $\underline{P_s}$ without corrections is 0.185 in. of water (46 Pa) and with duct resistance corrections is 0.105 in. of water (26 Pa).

This example demonstrates a typical case of how the DeltaQ equations fit the data. The true *Qs* is 157 cfm (74 L/s) and the values determined by DeltaQ are 170 and 146 cfm (80 and 69 L/s) for no corrections and with corrections respectively. The Q_r is 105 cfm (50 L/s), with DeltaQ determined values of 136, uncorrected, or 108 with corrections (64 or 51 L/s). The measured plenum pressures, where the leaks were located, were 0.165 in. water (41 Pa) at the supply plenum and –0.165 in. water (–41 Pa) in the return plenum. This data is from the "normal" envelope leakage case.

Introduction of the duct resistance correction terms changes the shape of the DeltaQ equation even if the values for $\boldsymbol{P_{\underline{s}}}$ and $\boldsymbol{P_{\underline{r}}}$ are unchanged. As seen in Figure 9 the inflection point at –0.229 in. water (–57 Pa) (the negative of the $\boldsymbol{P_{\underline{s}}}$ value in the uncorrected DeltaQ equation) has been shifted to a lower value of about –0.42 in. water (–110 Pa) yet the $\boldsymbol{P_{\underline{s}}}$ value, found by curve fitting, in both cases is 0.229 in. water (57 Pa).

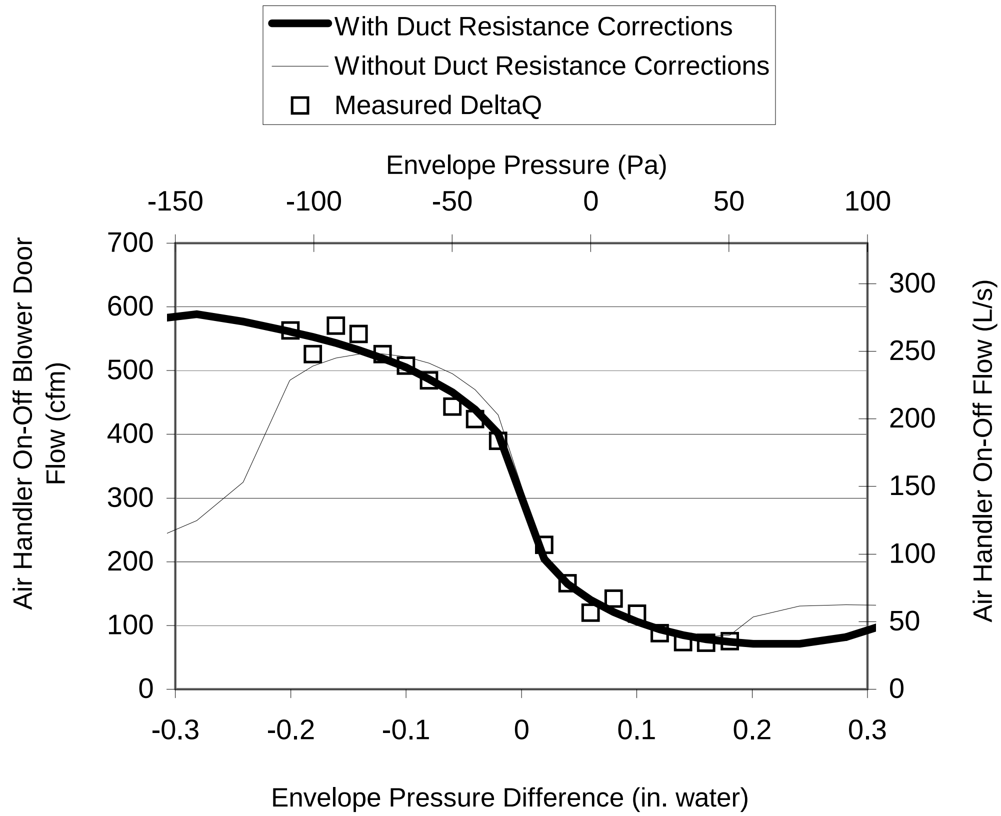

Figure 9: The DeltaQ equation with and without $\delta P_{r,s}$ corrections for a case where $\underline{P_s}$ remained unchanged.

Summary of Laboratory testing

A total of 37 measurements were made with the test chamber using the four duct leakage configurations and two different envelope leakage configurations. In this analysis the range of possible characteristic pressures was limited to be greater than the lowest measured envelope pressure (when pressurizing) and lower than twice the highest measured pressure. So for example if the data was taken every 0.02 in. water (5 Pa) from –0.2 to 0.2 (–50 to 50 Pa), $\underline{P_s}$ and $\underline{P_r}$ would be constrained to be within the range of 0.024 to 0.402 in. water (6 to 100 Pa). Table 1 shows the results of applying the duct resistance correction terms.

Table 1: Summary of DeltaQ analysis

	Q supply: average 136 cfm (64 L/s)		Q return: average 33 cfm (16 L/s)		Q total: average 169 cfm (80 L/s)	
	Average Error % of fan flow [cfm] (l/s)	RMS Error % of fan flow [cfm] (l/s)	Average Error % of fan flow [cfm] (l/s)	RMS Error % of fan flow [cfm] (l/s)	Average Error % of fan flow [cfm] (l/s)	RMS Error % of fan flow [cfm] (l/s)
ΔQ uncorrected	0.7 [7] (3)	1.9 [19] (9)	1.0 [10] (5)	2.1 [21] (10)	1.7 [17] (8)	3.9 [38] (18)
ΔQ corrected	-0.5 [-5] (-2)	1.8 [18] (8)	0.0 [0] (0)	1.8 [18] (8)	-0.5 [-5] (-2)	3.4 [33] (16)

Using the duct resistance correction improved the rms error somewhat, but more importantly, reduced the average total error from about 2% of fan flow to -1/2 % of fan flow.

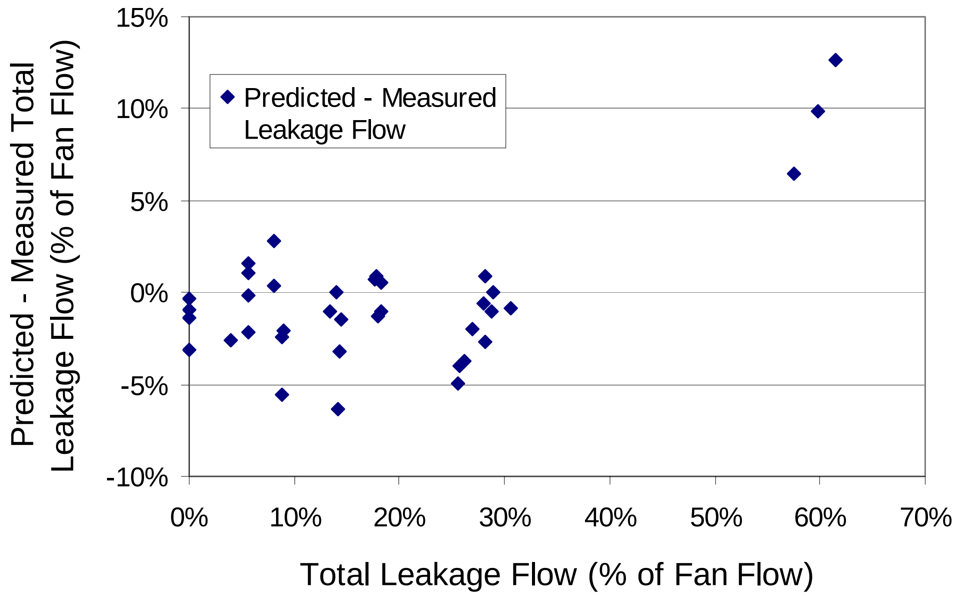

Figure 10: Duct resistance corrected total leakage flow.

The data in Figure 10 shows that the error in the total leakage flow is within 5 % of fan flow for most of the measurements. When the total leakage flow is greater than one third of the fan flow the errors increase but there is not enough data (only three points) to determine if this represents a trend or simply an increase in scatter. If the aim of the measurements is to decide if the duct system is leaky these larger errors do not matter because the duct system is definitely leaky and these larger errors would not affect any decisions about the duct system to be made based on the test results (e.g., should ducts be retrofitted or do they pass a minimum leakage specification for a new system).

DISCUSSION

The DeltaQ test uses standard blower door test methods to provide an accurate method for determining duct leakage to outside. All duct leakage measurement techniques make the assumption that the resistance of the ducts can be ignored and therefore have a bias. The size of the bias depends on the specifics of the technique and the size and distribution of the leakage.

Duct pressurization, for example, suffers not only from the “fan-off” bias, but also from additional biases associated with moving large amounts of air through a stopped air handler. The bias could, in principle, be removed by measuring the applied pressure at the leak. Unfortunately, even if the leaks were concentrated at one place, one would have to know where that was to make the proper measurement. A careful pressure mapping of the entire duct system could also be used to infer the leakage distribution, but such a procedure is well beyond what could be expected of a field technician. For most of the duct pressurization techniques, the best that can be done is to bound the bias. A detailed comparison of the errors associated with different techniques is beyond the scope of this report.

As seen in Table 1 the results of the laboratory testing show a 17 cfm (8 L/s or 2% of fan flow) bias in the uncorrected DeltaQ assessment of total leakage flow. This is a lower bias than has been reported before by Walker et al. (2002, 2001and 1998) and Francisco (2002). We believe that this is at least partly a result of taking data points up to 0.20 in. water (50 Pa) whereas previous measurements were often taken only to 0.10 in. water (25 Pa).

Application of the duct resistance corrections lowers the average bias to –5 cfm (-2 L/s or -1/2% of fan flow). The RMS errors are also somewhat reduced. As seen in Figure 10, the error in the total leakage flow appears to be somewhat biased low until the leakage level is above 30% of fan flow. At this point the errors increase and may become biased high. This may indicate the need for different corrections with revised assumptions.

An estimate of the air handler flow is necessary to make the duct resistance corrections. We found that the predicted leakage flows were not very sensitive to the uncertainty in this value unless the leakage flow was larger than half the fan flow. It should be good enough to get the air handler flow from nameplate information or a simple guideline of 400 cfm/ton of air conditioning.

Application of the pressure biases correction, that accounts for the possible pressurization or depressurization of the building by the unbalanced leakage flow, lowered the average total leakage flow by 2 cfm (1 L/s), and by 14 cfm (7 L/s) in the most extreme case where $\boldsymbol{Q_{\underline{s}}}$ was lowered by 19 cfm (9 L/s) and $\boldsymbol{Q_{\underline{r}}}$ increased by 5 cfm (5 L/s). As expected, this correction is minor.

Further work needs to be done to reliably use the DeltaQ method in cases of high envelope leakage, where only limited envelope pressures can be achieved, and/or leak pressures that are much greater than the envelope pressures used in the existing DeltaQ technique.

The results of the DeltaQ analysis for 37 tests from a laboratory test chamber show an initial bias of 2% of fan flow. This is lower than previously seen and is attributed in part to acquiring more data at a wider pressure range. Application of the duct resistance corrections to this data lowers the bias to -½% of fan flow (-3% of average leakage flow). The corrected DeltaQ RMS errors also show a slight improvement from 3.9% to about 3.4 % of air handler flow. This is approaching the lower limit of what we can expect to be able to resolve given the accuracy of our instrumentation: the calibration of the blower door is also about +-3% of flow.

CONCLUSIONS

Careful experimental and theoretical analysis of the standard DeltaQ model has shown that there are some intrinsic biases created by the simplifying assumptions of the model. We have developed and experimentally tested improvements to the standard DeltaQ model that help minimize the error:

- To minimize the error associated with the not knowing the location(s) of the leak sites, the supply and return leak pressures should be treated as a free parameter in the model
- Unbalanced duct leakage can interact with envelope leakage to create a bias. This bias can be simply corrected using the blower-door information that is generated by DeltaQ. (See equations 5-7)
- Flow resistance in the ducts causes a bias, which should be corrected for using the equations found in the “CORRECTING DUCT RESISTANCE BIASES” section and an estimate of the air handler flow.

These corrections are found to improve the accuracy of the model without substantial numerical penalty—especially when prior knowledge is used to keep fit parameters inside physically reasonable bounds. Individual tests will still have precision errors due to scatter and systematic errors when other assumptions are substantively violated. Such precision errors will be the dominant uncertainty in most field experiments.

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